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Final Report for Phase II of:

"Advanced Fibers, Anti-Friction Materials and Jackets for Navy Ropes"

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Table of Contents

1 Background 3
2 Research Summary 4
  2.1 Summary of Project Objectives 5
    2.1.1 Base Tasks: 6
  2.2 Cost summary 7
  2.3 Summary of project accomplishments 7
3 Project Activities and Findings 7
  3.1 Fiber Testing 7
    3.1.1 Summary 7
    3.1.2 Fiber Tester design 8
    3.1.3 Fiber Test Results 10
  3.2 Yarn Testing 11
    3.2.1 Yarn Tester design 11
    3.2.2 Yarn Test Results 12
  3.3 Rope Testing 14
    3.3.1 Rope Tester design 14
    3.3.2 Rope Test Results 15
4 Rope Health Monitoring 16
  4.1 Predicting rope failure 16
  4.2 Tests Results 17
5 FEA Modeling 18
6 Investigation of alternative materials 21
7 Conclusions 21

1 Background

The research funded by this STTR project addresses the US Navy's desire to develop a new generation of synthetic ropes for running rigging based on advances in fiber materials, surface treatments, protective coatings and attendant manufacturing methods. Currently existing synthetic ropes exhibit tensile strength and axial stiffness similar to that of wire ropes, yet with lower weight and greater flexibility. Where they fall short is in their resistance to crushing, abrasion, wear, creep, and thermal degradation.

The advantages of synthetics over wire ropes are substantial. The tensile strengths of various fibers (Aramids, PBO, LCP and UHMWPE), are typically about 3 GPa (440 ksi), which is significantly higher that that of highly drawn steel wires (1.7 GPa). Their densities are lower than steel wire by a factor of about 5 while the axial fiber stiffness approaches that of steel wire. Thus, for a given axial rope stiffness and strength, there is the potential for large weight savings and a reduction in bending stiffness. Achieving such gains, however, presents major technical challenges due to the relatively low transverse strength and abrasion resistance of synthetic fibers compared to steel wires.

Steel wires are nearly isotropic in stiffness and strength. They are highly drawn to maximize yield strength, yet still exhibit some ductility in tension. In transverse compression, perpendicular to the wire axis, the ductility and yield strength are close to their tensile values. In transverse and 'short-beam shear', their yield strengths exceed 0.5 GPa. These properties are desirable and important in ropes or cables. Due to the helical structure, rope tension induces transverse Hertzian contact stresses between the wires, which increase with rope diameter and are largest at the center. Ropes are also subject to transverse compressive loads due to contact with sheaves, bollards, anti-slack devices and temporary clamps. Such loads increase these contact stresses and, during bending, shear sliding and large shear stresses develop. Lubricated steel wires perform very well in these circumstances.

Polymeric (synthetic) fibers, on the other hand, are highly anisotropic in stiffness and strength. In the transverse direction they are much lower in compressive stiffness and yield strength than in axial tension – by a factor of 10 to 30. They can, however, accommodate fairly drastic transverse deformation, which tends to be plastic-like under a low yield strength, and still can support extremely high tensile stresses. For example, Phoenix and Skelton showed that the aramids Kevlar 29 and 49 have a plastic yield strength of about 45 MPa in shear, compared to their tensile strength of about 3,000 MPa - a 75:1 ratio. Furthermore, Kevlar fibers may be deformed transversely into a ribbon shape, yet still retain about 75% of their tensile strength. In addition to having low shear yield strength, the tensile strength of Kevlar fibers is reduced when both shear and tension act simultaneously. Other successful fibers, UHMWPE and PBO have similar behavior to Kevlar, though are less susceptible to splitting. In summary, the transverse mechanical strength and stiffness of synthetic fibers are lower than those of steel wires by at a factor of more than 20, a fact that results from their molecular structure.

The drastic differences in transverse properties of steel wires and high-strength polymer fibers have several consequences in rope performance: First, upon initial tensioning of a synthetic rope, permanent elongation or 'stretch' occurs that does not occur in steel ropes to the same extent. Between fibers, the Hertzian compressive stresses are large enough to induce permanent deformation and the fibers lose their roundness as they pack together tightly. Consequently the rope diameter permanently decreases, thus elongating the helix structure. By itself, this deforma-

tion is not detrimental. However the contact stresses and friction state between fibers is changed, thus increasing fibrillation tendencies under cyclic bending or in rolling sheave contact.

Second, reeling such a cable under high tension onto a drum to form several layers may 'crush' the rope transversely and severely distort the rope cross-section even causing strand pop-out. At small-angle crossovers, packing will be random and undercutting may occur. This crushing induces circumferential slip between rope layers, and the shear stresses created can cause oblique shear failure of fibers not to mention distortions that hinder reeving the rope over sheaves.

Third, the rope or cable cannot easily be gripped over short lengths by steel jaws without damaging the outer fibers and strands – a problem that is largely absent in steel wire ropes. Not only do crushing pressures occur, the shear stresses lead to fiber splitting.

Fourth, the molecular structure that leads to the low transverse stiffness and yield strength also reduces the wear and abrasion resistance compared to steel wires. The fibers are prone to fibrillation under excessive shear stresses during sliding.

If the performance of synthetic ropes is to be improved then failures arising from the low transverse strength and stiffness must be addressed. The work completed in phase II shows that protecting the outer surface of the fibers, by surface modification, friction reduction, or encapsulation, can lead to dramatic increases in the performance of synthetic ropes.

2 Research Summary

While there are new developments in fiber materials (e.g. M5) there are no radically new materials ready for large-scale commercial production that will approach the transverse mechanical properties of steel wire. M5 fibers may give gains in transverse yield strength and stiffness that are a factor of 2 to 5 over current fibers but will remain close to an order of magnitude below those of steel wires. Their resistance to splitting due to simultaneous tension and shear as well as their abrasion resistance may also be improved by a factor of 2 or 5, but this will depend on molecular aspect ratio resulting from the spinning process.

Although the potential gains are all very beneficial, they fall far short of making such materials "plug-in" replacements for steel wires in all applications. In other words, there is no new fiber material on the horizon that is mechanically equivalent to steel wire. This implies that, while new polymer fiber materials may offer incremental improvements over existing fibers, other approaches, such as surface modifications, protective coatings or permanent lubricants will still be needed. All three approaches have been used in this project:

(1) chemical and plasma etching has been used to modify the surface of fibers in an attempt to produce a "case" that is resistant to fibrillation and shear fracture;

(2) viscoplastic and viscoelastic coatings have been applied to yarns and fibers by solution coating and vapor deposition in order to reduce friction and increase abrasion resistance; and

(3) lubricants such as silicone greases have been tested in yarns and fibers as a means to reduce friction and heating.

Each approach has the potential to benefit any of the synthetic fibers mentioned above since they all exhibit similar failure mechanisms. All of these fibers are highly aligned, long chain molecules with relatively weak hydrogen bonds linking adjacent molecules. Thus, experiments have

been completed on Kevlar (an aramid), Spectra (an ultra-high molecular weight polyethylene or UHMWPE), Zylon (polybenzoxazole or PBO) and Vectran (a liquid crystal polymer or LCP).

Single fibers have been tested extensively, using a custom designed device, in order to isolate geometric effects that occur when testing yarns. Yarns were subsequently tested using an ASTM abrasion tester. Test results are summarized below.

- Improvements in the performance of Kevlar were minimal. Failure appears to be driven by the number of fibrils present immediately after manufacture.
- Lubrication had a dramatic effect on the abrasion resistance of Vectran (LCP) and Spectra (UHMWPE) yarns. Life increases of more than a factor of 20 were achieved in ASTM tests. Migration of lubricants appears to be a limiting factor.
- Surface modification alone produced some improvement in Vectran and Spectra abrasion resistance. This is thought to be due to cross-linking in the outer skin.
- Fluorination did not produce any significant improvement through friction reduction.
- Hot water soak (55°C, 24 hours) significantly reduced the life of treated Vectran and Spectra yarns. However, coating the treated yarns with polyurethane prevented degradation in hot water almost completely without sacrificing dry abrasion resistance.
- Solution deposition of AAA in 3/8" braided ropes yielded only a 2X increase in bend-over-sheave life. No dependence on solution viscosity was observed. Poor wetting of the rope is hypothesized. Coating at the yarn level is necessary if fatigue life is to be maximized.
- Increases in rope stiffness and loss-factor were demonstrated with untreated 3/8" ropes. This holds promise as a means to predict wear-out in synthetic ropes.

In the phase II option we propose to test 3/8" Vectran and Spectra ropes that have been treated at the yarn level in bend-over-sheave fatigue. As these ropes are tested the loss-factor will be monitored to determine whether wear-out can be accurately predicted. A new solvent will be used in order to eliminate concerns with volatility that has been raised by manufacturers.

2.1 Summary of Project Objectives

The overall objective of phase II is to develop a synthetic rope that is significantly more robust than existing ropes, approaching the strength and resistance to damage of wire rope, while maintaining the substantial advantages of synthetics - low weight, greater flexibility, longer fatigue life and minimal maintenance. This will be accomplished by research on materials, surface treatments, coatings and structure at the fiber, yam, strand and finished rope levels. After complete testing with 3/8" diameter ropes the contractor will select up to five candidate constructions for testing in 1" diameter. Testing these ropes in legacy systems will be undertaken as an option during phase II; fabrication of test facilities for larger ropes will be undertaken as an option for transition to phase III. In addition embedded sensors within the rope will be developed and demonstrated to anticipate impending failure.

2.1.1 Base Tasks:

1. To evaluate new materials not available within phase I such as MS. Investigate biological polymers from cyclic amino-acids which may have superior inter-molecular bonding. Investigate interaction between materials enabling fiber blends within larger rope structures.
2. To improve the abrasion resistance of the rope at all levels using protective surface coatings and surface modification. Fibrous jackets made of abrasion resistant materials will be improved at the strand and rope levels. These improvements will lead to reduced fibrillation within the rope and will protect its exterior wherever it is in direct contact with fairlead or trolley sheaves, bollards, bulwarks and other hard objects.
3. To develop coatings or surface treatments for yarns that will reduce inter-fiber friction, allowing movement within rope components while reducing transverse traction forces.
4. To devise visco-elastic and visco-plastic coatings to be applied to fibers, yarns or strands to reduce fibrillation or splitting as they move within a rope. Treatments will remain in place under high transverse pressures, and at elevated temperatures from frictional sliding, so that rope properties do not degrade during their lifetime. Any material on the rope's outer surface will not reduce the friction coefficient between the rope and any tensioning equipment.
5. To quantify environmental effects on rope at appropriate' structural levels. UV degrades aramid fibers at much different rate than LCPs. Moisture is likely to have an effect on adhesion of any surface coatings. Crystallization of salt within rope may accelerate internal abrasion and wear.
6. To determine acceleration factors for testing at elevated temperatures, reduced bending radii, and increased tension. Excess heat generated within a rope is known to cause premature failure and is a particular problem in large diameter ropes. Bending over small diameter sheaves at high tensions significantly reduces rope fatigue life. Quantification of these effects for different constructions and materials will accelerate testing.
7. To develop cost-effective strategies for redesign, retrofit or resurfacing of rope pathway components such as sheaves, bollards, bitts and, anti-slack devices. Movement with a rope when it passes around a sheave or when traversed by a load supported by a sheave causes damage. Sheave diameter and groove geometry will be studied.
8. To develop models for surface traction and rope slip around pathway elements. This will seek to improve upon the model for tension that can be applied by a traction sheave as expressed by the equation T1/T2 = eJ.lC which, although useful, conveys no information about the local tension in the rope as it passes through the sheave.
9. To develop models of rope deformation within rope pathways. Special, semi-analytical discrete element models that have a multiscale architecture will be developed. Similar models will be used to predict the generation of heat from hysteresis within fibers and from friction during slip of rope components.
10. To embed sensors within the rope to monitor damage and remaining life. Such sensors will be continuously readable from the supply ship. Single-mode optical fibers doped to exploit Bragg diffraction or copper wire tested using time-domain reflectometry have

been shown to be useful in determining strain or geometric discontinuities. The contractor also proposes the use of multi-mode fibers that can be monitored for wear of the cladding layer. Demonstrate that rope failure can be predicted using these sensors.

2.2 *Cost summary*

Labor costs were determined by an audit by Michael Doyle of the DCAA NNJ Branch Office, Johnson City, NY in June, 2003. Standardized labor rates of $24.23/hour for engineering and scientific staff and $12.44 /hour for manufacturing were used with an overhead rate of 115%. G&A has been charged at 8% of total labor costs.

Table 1: Cumulative project costs	Cost
ADC Direct Labor	$95,440
Overhead (115%)	$109,756
Direct Materials Costs	$96,591
General and Administrative Expenses 8%	$23,944
Fixed Fee of 5%	$15,549
Cornell University	$14,800.00
Binghamton University	$138,610
Cumulative Total:	$492,210

2.3 *Summary of project accomplishments*

Advanced Design Consulting with the help of Binghamton University completed a large matrix of testing on different coating to synthetic ropes fibers, yarns, and ropes. We have now created a coating at the yarn level that has increased the bend-over-sheave results by over 30 times compared to the baseline. This coating when applied directly to an already woven 3/8" rope gives us only a 2 times increase compared to the baseline. We now have stepped back and are coating large quantity of yarn to have woven into a rope. This allows us to certain that all the individual fibers in the rope have been adequately coated.

3 *Project Activities and Findings*

3.1 *Fiber Testing*

3.1.1 Summary

A test methodology was been developed for simulating the damage that occurs to individual fibers within a rope as it is deformed. A tester was been designed and constructed and initial samples prepared. This is an open-loop control; however, a double-beam load-cell was designed for use with this tester and is currently under construction.

3.1.2 Fiber Tester design

Failure of synthetic ropes generally begins with wear as fibers move against one another. Whether this movement is between strands, the yarns within a strand or between individual fibers the result is similar: fibrillation. Hydrogen bonds between the highly-aligned molecules break resulting in fractures that propagate at extremely shallow angles. In order to study this phenomenon in a well-controlled manner we are conducting initial experiments on individual fibers. In these experiments the contact stress, relative displacement, velocity and fiber tension can be independently controlled. The small size of the samples minimizes frictional heating.

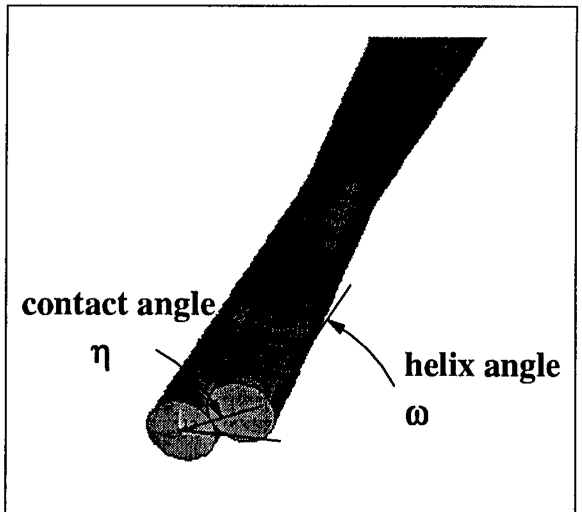

Figure 1: Helix angle and contact angle defined for test geometry.

The geometry chosen for these experiments is similar to that used in wire-ropes. A single, straight fiber is surrounded by six fibers of the same cross-section that are wound about it at a helix angle – as shown in Figure 1. In the absence of friction a contact force of *2Tcos(–)/d* per unit length is applied to the test fiber by each of the six surrounding fibers, where *T* is the tension in each of the surrounding fibers and *d* is the fiber diameter.

Hertzian contact stresses can be calculated from these parameters and adjusted within a wide range to simulate conditions within a rope as it is bent under tension. For Kevlar 29 fibers with a 10 μm diameter a mass of 4.5 grams per fiber produces a stress of about 15% UTS. Masses of from 18 to 90 grams can be used to tension the six outer fibers in the tester.

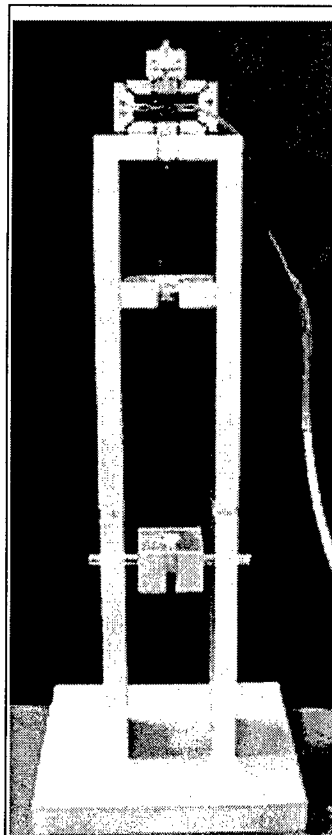

Figure 2: Fiber tester.

Tension is applied to the outer fibers by a suspended mass as shown in the photograph of the tester in Figure 2. Initial tests are being conducted with a mass of 27 grams. The weight has guide pins that run in vertical slots within the tester in order to prevent the array of fibers from untwisting. Since the moment that they apply is very small, and the contact in the slot is far from the center of rotation, the friction force is negligible. In addition to guide pins the weight is provided with a slot to allow the sample to be mounted. This slot destroys the symmetry of the weight which must be compensated for by skimming the opposite surface. Balance has been checked by supporting the weight on knife-edges at the guide pins.

In order to apply uniform tension to the six outer fibers the specimen must be assembled with extreme care. An assembly fixture, shown in Figure 3, has been constructed to ensure that fiber

lengths are equal.

The outer fibers are first threaded through holes in a reusable, square brass mount. An adhesive is then injected into the holes and allowed to cure overnight (silicone was initially used although gap filling cyanoacrylate has been found to be preferable). The fibers are then threaded through a second mount and a 50 mg mass is attached to each fiber. Next the sample is transferred to the assembly fixture. Adhesive is then injected into the unfilled holes while the fibers are held under tension by the attached masses.

The test specimen is then threaded through the center hole in each of the brass mounts. Both ends of the specimen are then mounted in half-inch long, 1/16" OD tubes using cyanoacrylate adhesive.

Once the adhesives have cured the prepared sample is transferred to the tester. The upper mount fits into a square recess that prevents it from rotating. The lower mount is then rotated the desired number of turns to produce the required helix angle. While the lower mount is being held the tensioning mass is slid into the guide slot and lowered into position.

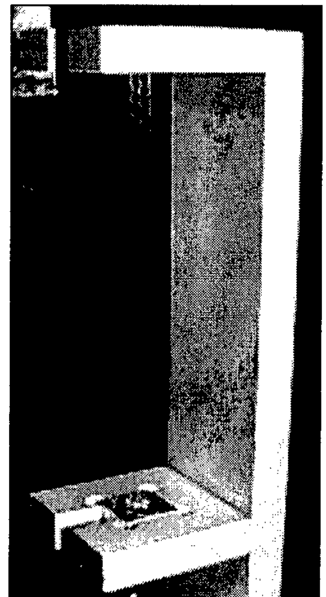

Figure 3: Assembly fixture.

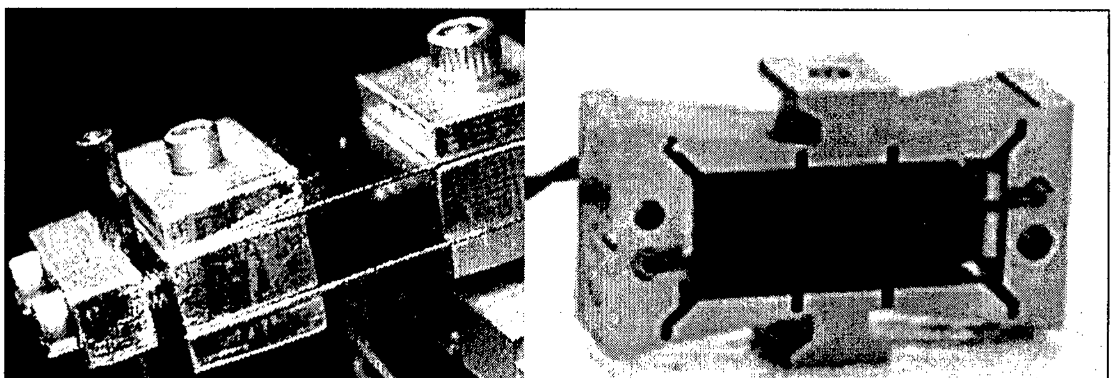

Figure 4: (left) Double-beam load-cell with test fiber mounted in hypodermic tube and (right) mechanically amplified piezo-electric transducer.

One end of the test sample is then clamped into the piezo-electric driver as shown in Figure 4. This driver uses a mechanical amplifier to produce a displacement of 100 microns. Between the clamp and the driver is a double-cantilever flexure that will be used as a load-cell. Strain gauges will be mounted above the upper flex and below the lower flex in a half-bridge arrangement so that the load applied to the test fiber can be monitored.

It is important to be able to measure the tension applied to the test fiber during testing. Frictional forces will increase the tension in the test fiber and decrease it in the outer fibers as the test fiber is pulled upwards. Rotation of the outer fibers and the progressive decrease in their tension further up the helix will at some point cause slippage and a redistribution of twist. Tension data will enable us to verify models of the interaction between fibers to ensure that the test conditions duplicate the environment within ropes.

At present we plan to run the initial tests at 10 Hz and 100 μm displacement. This will allow nearly one million cycles to be applied per day. Residual strength measurements will be used to determine the damage. Fibers will also be examined using SEM for qualitative evaluation of wear.

3.1.3 Fiber Test Results

Kevlar:

Wear doesn't respond much too any type of treatment we've tried:

- plasma, wet chemical surface modification + fluorosilane

- pdms/teos + polyurethane

- silicone greases, oils, lubricants

- abrasives mixed with pdms/teos coatings

- pdms-2000/teos mixtures may be somewhat effective.

- Suspect that Kevlar failure is dominated by entanglement of pre-existing fibrils.

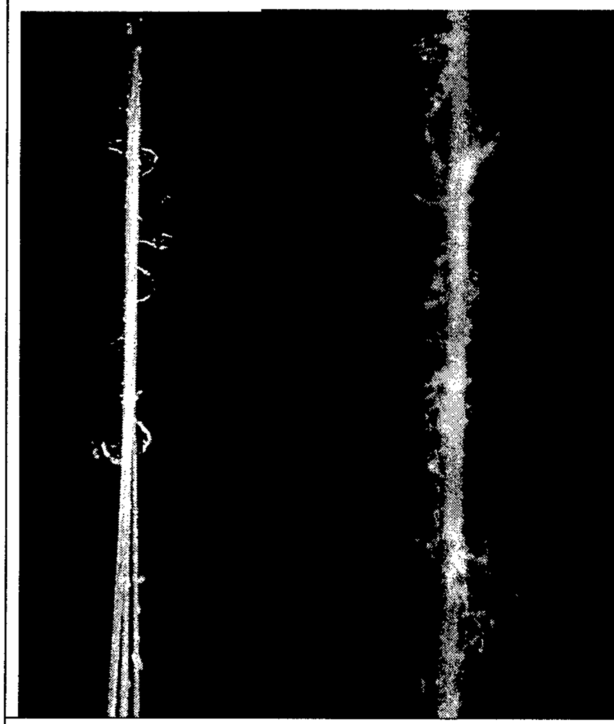

Figure 5: Untreated Kevlar after 1 million cycles (left) and 5 million cycles (right) still mounted in wear tester.

Vectran:

Oxygen plasma + solution deposited fluorosilanes

- wear exceeded baseline values in some cases

- not yet reproducible

- suspect that good results are due to contamination (not proven)

- clear improvement in wear vs. acetone cleaned yarn shows that coating is occurring in many cases.

- vapor deposited fluorosilanes gave very poor results.

Viscoelastic coatings can greatly improve wear life

- silicone greases and oils

- pdms alone, and pdms + teos

- 24 hour hot water degrades performance

- addition of polyurethane coating over pdms greatly improves resistance to degradation in hot water.

Spectra:

- best wear life of all yarns tested
- both as-received and after coatings.
- same kinds of things that work for Vectran also work for Spectra
- important since we want to use the BOB rope from Cortland Cable and apply a single treatment to a mix of Vectran and Spectra.

Zylon:

- few results, but no indication that wear life is comparable to Vectran, Spectra.
- silicone grease improves wear (unlike Kevlar)
- could try with the pdms/teos approach to take advantage of its lower weight.

The conclusions in fiber testing have proven difficult on Kevlar and did not produce any meaningful results on Vectran, Spectra and Zylon using equivalent testing parameters. Even though a large amount of data was collected on Kevlar fibers with various treatments, the variability of the data suggests that these tests are largely non-repeatable. Rarely will identical fiber tests yield results within acceptable standards of deviation. Fiber testing was discontinued in favor of yarn testing which utilizes a widely accepted industry test standard (Cordage Institute Standard CI-1503) and yielded repeatable test results.

3.2 Yarn Testing

By testing yarns containing many fibers we are able to evaluate coatings and treatments in a manner that more closely resembles an actual rope. The testing that has been done to yarns which are made up of multiple fibers has resulted in reduced variation between similar samples. This is because variations in the strength of individual fiber will have a small effect on the net strength of the yarn as a whole.

3.2.1 Yarn Tester design

The yarn testing is based on the standard developed by the Cordage Institute (CI 1503) and adopted by ASTM under D1776. This testing is strictly comparative in nature. Figure 6, shows a diagram of the standard yarn abrasion test. Figure 7, shows a photograph of the yarn tester. This machine will accommodate 4 yarn samples and test them simultaneously. Digital counters located on the top faceplate totalize cycles to failure of each test individually. Controls can be set to automatically shut the machine down if either 1 yarn fails or if all yarns fail. Tests can be performed wet or dry. A beaker containing wet test solution can be placed at each of the 4 test stations. During the environmental testing phase, salt water can be used to gain data on the performance of promising yarns in a seawater environment. Additionally, yarns can be saturated in brine and dried several times and tested dry to simulate splash zone performance. It is expected that good yarn-to-yarn abrasion performance correlate to good bend-over-sheave performance.

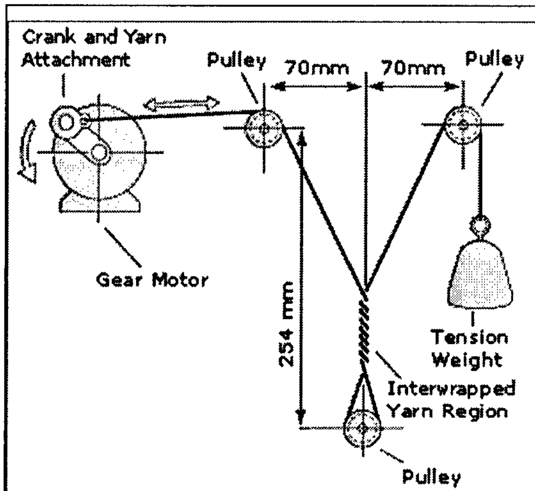

Figure 6: Yarn abrasion test diagram

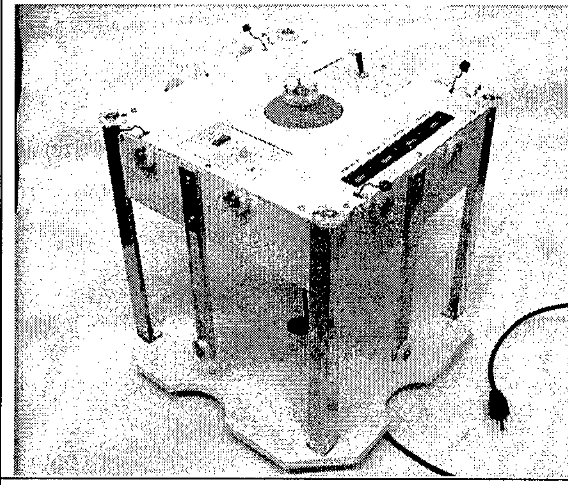

Figure 7: Yarn-on-yarn abrasion tester

3.2.2 Yarn Test Results

Of the rope coatings tested in phase II a single rope coating has been identified as the best candidate because of its extraordinarily good test results and the chemicals used in the coating solution make a minimal impact to the environment.

The identified solution is a "10/6 solution", 5% TEOS, 15%PDMS in Di (propylene glycol) dimethyl ether. The below are the results when using the identified solution on the coating of a Vectran yarn. These results show in Figure 8 have shown a large increase in the time to failure and can be continually repeated.

The test is standard developed by the Cordage Institute (CI 1503) and adopted by ASTM under D1776

Yarn	PDMS used	composition of solution	PU (y/n)	description of treatment	Average Failure Cycles
Vectran		As received from factory, twisted yarn, 60 tex	n/a	none	**229**
Vectran		As received from factory, twisted yarn, 60 tex - wrapped RH on tester	n/a	none	**215**
Vectran		As received from factory, untwisted yarn, 110 tex	n/a	none	**264**
Vectran	90- 150cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	1:4 olympic PU coating	in 10/6 soln. Sit out 5 min in oven (120℃) 10 min 1:4 PU coating sit out 1 min in oven (120℃) 15 min	**15053**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	1:4 dilution olympic Plus 0.3113g talc	Run thru 5, 15 once bake: 8m, run thru PU, 7m @115℃	**23909**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	1:4 olympic dilution	Run thru 5, 15 once bake: 8m, run thru PU, 7m @115℃	**29287**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	n/a	Run thru 5, 15 once bake: 10m, RW, 10m @120℃ RT Sea water w/SB time=27 hours bake 12m @115℃	**13062**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	n/a	Run thru 5, 15 once bake: 10m, RW, 10m @120℃	**19914**
spectra	550 MW	30% PDMS, 10% TEOS in Ethanol	1:4 dilution	hot sea water (55℃) time = 21 hr, 30min	**85933**
Vectran	90-150 cSt.	5% TEOS, 15% PDMS in THF	n/a	Run thru 5, 15 once bake: 5m, RW, 8m @110℃	**20645**
Vectran	90-150 cSt.	5% TEOS, 15% PDMS in THF	n/a	Run thru 5, 15 once bake: 10m, RW, 10m @105℃	**28231**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	n/a	Run thru 5, 15 once bake: 12m, RW, 12m @110℃* <sample allowed to sit out before first wrap and bake>	**28137**
Vectran	90-150 cSt.	"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	n/a	Run thru 5, 15 once bake: 12m, RW, 12m @110℃* <sample allowed to sit out before first wrap and bake>	**29447**

Figure 8: Vectran test data using a "10/6 solution", 5% TEOS, 15%PDMS in Di (propylene glycol) dimethyl ether coating. The average is a compiled of four yarn stations.

3.3 Rope Testing

3.3.1 Rope Tester design

The long-term goal of our fiber testing is to develop treatments/coatings that will reduce wear and extend the life of synthetic ropes. Final assembly of our rope tester (Figure 9) has recently been completed. This is a significant milestone for the rope project. With the addition of our rope testing capabilities we can now design ropes based on the results of our fiber tests. The rope tester as it is currently configured is capable of creating over 3,000 lbs of tension in a 3/8" diameter rope. A trolley containing three sheaves traverses the rope sample with 20" of stroke. There is a load cell attached to the linear actuator that will measure the frictional losses in the sheaves and rope system. As rope wear progresses there is predicted to be a stiffening of the rope. This increased stiffness will show up as increased friction over the pulleys.

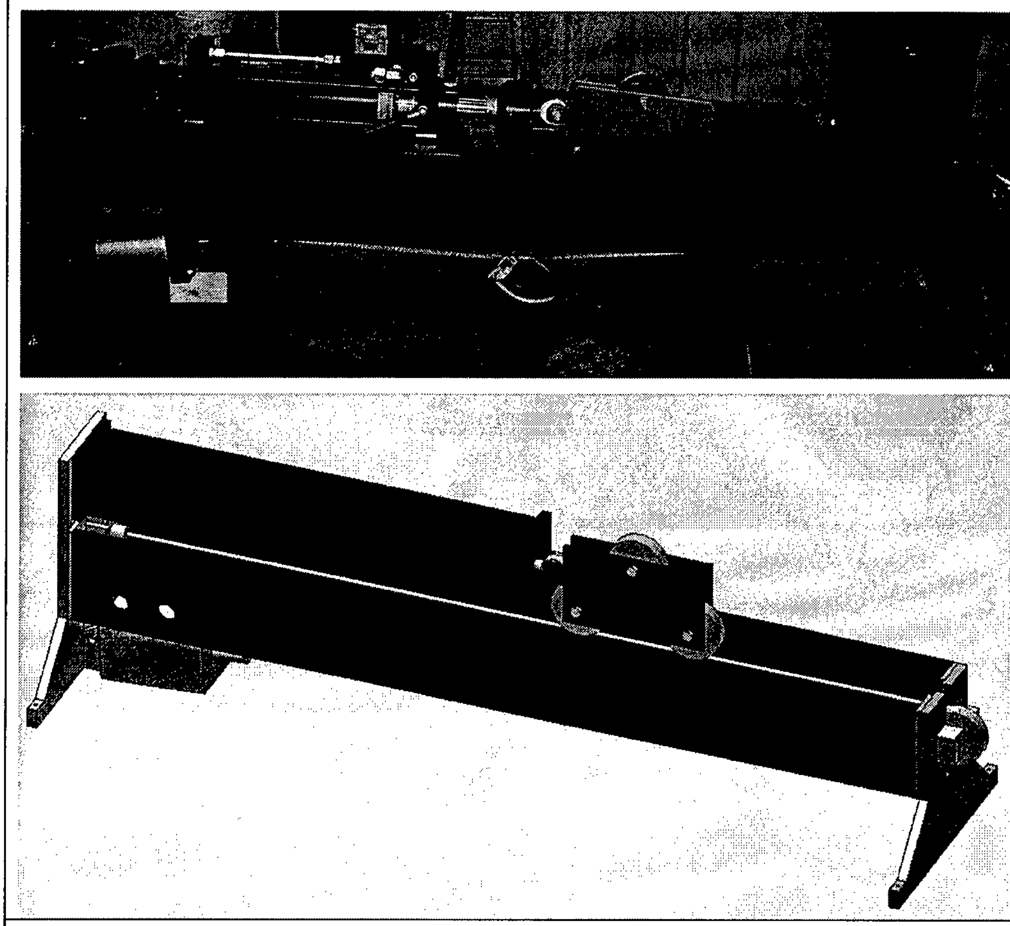

Figure 9: Rope tester after assembly (top) and as Designed (bottom).

3.3.2 Rope Test Results

Rope tests were performed on Spectra, Vectran, and IWCR wire rope. All these tests were done on 3/8" diameter ropes. Under the same load the off the shelf unjacketed Spectra and Vectran had a similar failure rate though the wire rope lasted by an increase of 2x in cycles to failure.

The Vectran and Spectra were both coated in the TEOS/PDMS solution at the rope level. This did increase the life of the rope by a factor of 1.5 to 2 but did not show the great results we saw in the yarn tests. The reason for this is that the coatings may not have penetrated down into the rope to the yarn level of each strand.

3/8" Rope Tests Results

I.D.	Treatment	Breaking Strength (lbs)	Load (lbs)	% Breaking Strength	Cycles to Failure
Vectran, 12 Braid, 3/8", no jacket					
Vectran Factory	As Received	21000	3165	15%	840
Vectran Factory	As Received	21000	3165	15%	2338
Vectran Factory	As Received	21000	3165	15%	2025
Vectran Solution Coated	5% TEOS / 15% PDMS	21000	3165	15%	5112
Vectran Solution Coated	5% TEOS / 15% PDMS	21000	3165	15%	3727
Vectran Solution Coated	25% PDMS/TEOS	21000	3165	15%	2753
Vectran Vacuum Coated	5% TEOS / 15% PDMS	21000	3165	15%	4313
Vectran Vacuum Coated	5% TEOS / 15% PDMS	21000	3165	15%	2802
Spectra, 12 Braid, 3/8", no jacket					
Spectra Factory	As Received	15300	2295	15%	2500
Spectra Factory	As Received	15300	2295	15%	4716
Spectra Factory	As Received	15300	2295	15%	4332
Spectra Factory	As Received	15300	3165	21%	2400
Spectra Factory	As Received	15300	3165	21%	2301
Spectra Factory	As Received	15300	3165	21%	2199
Spectra Vacuum Coated	5% TEOS / 15% PDMS	15300	2295	15%	3469
Spectra Vacuum Coated	5% TEOS / 15% PDMS	15300	2295	15%	2805
Wire Rope, 6x37, 3/8", IWRC					
Wire Factory	As Received	13120	1968	15%	9090
Wire Factory	As Received	13120	1968	15%	9877
Wire Factory	As Received	13120	3165	24%	3983
Wire Factory	As Received	13120	3165	24%	4472

4 Rope Health Monitoring

4.1 Predicting rope failure

A way to measure rope stiffness is to use a lightweight "dancer" sheave as shown in Figure 10. This uses a drive sheave rotating at a constant velocity, a test sheave or "dancer" whose vertical position is continuously monitored, and a slave sheave that is controlled by feedback from the dancer. The control network is set up to use the displacement, velocity and acceleration of the test sheave to modify the rotational speed of the slave. Changes in the test sheave position, which can be produced by a stiff section of rope passing through the system, create an error signal that can be monitored and recorded. Such a system would be useful for in-situ tests wherever synthetic ropes are used.

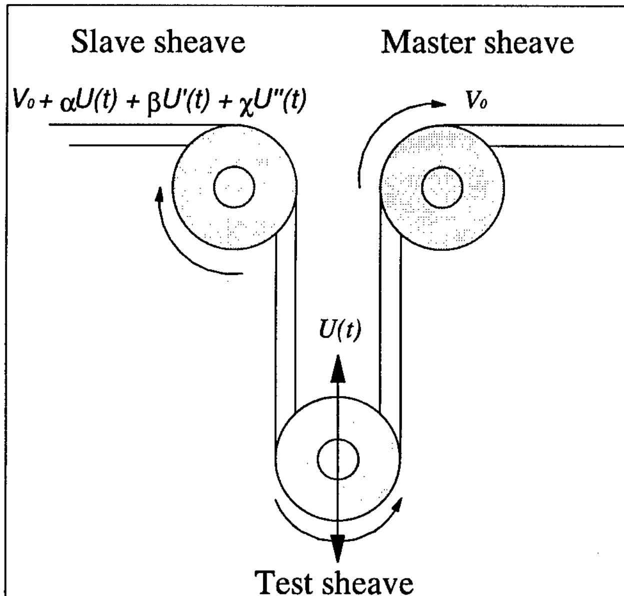

Figure 10: Technique for monitoring rope stiffness.

Dynamic measurements can be made on a rope using a LED / photo-diode pair in reflection mode to monitor the transverse vibration of the rope after an impact with a light-weight hammer. The time-domain signal was then converted to the frequency domain using Fourier transform and the losses within the rope over the measurement section were characterized by the Q-factor.

Q-factor is defined as the ratio of the center frequency of a resonance to the width at the half-power points (also known as the 3dB-down points). Since this relies on the shape of the resonance peak the magnitude of the impact to the rope is unimportant, provided that it is large enough to avoid signal-to-noise problems but not so large as to violate small-angle restrictions.

A diagram showing the test geometry is shown in Figure 11. A rope fixed at one end, passed through three 5.25" diameter sheaves in a trolley, and attached at the other end to an air cylinder. A tension of about 1880 lbf is applied to the rope. A servo-hydraulic cylinder is used to move the sheave trolley over a 6" stroke. After cycling the sheave trolley was retracted leaving a wear section of about 18" within a total test section of 31".

Full tension was maintained on the rope during each measurement. A series of five measurements were averaged at each test interval. The Q-factor was initially very high – about 70 – but decreased almost immediately to a value of about 26. After this the Q decreased monotonically to about 8000 cycles reaching a minimum of about 20. From 8000 cycles on the Q increased once again. This increase occurred just prior to failure at 8900 cycles. The section of rope where failure occurred is the 2 bends/ cycle section on the left sheave, shown in Figure 11.

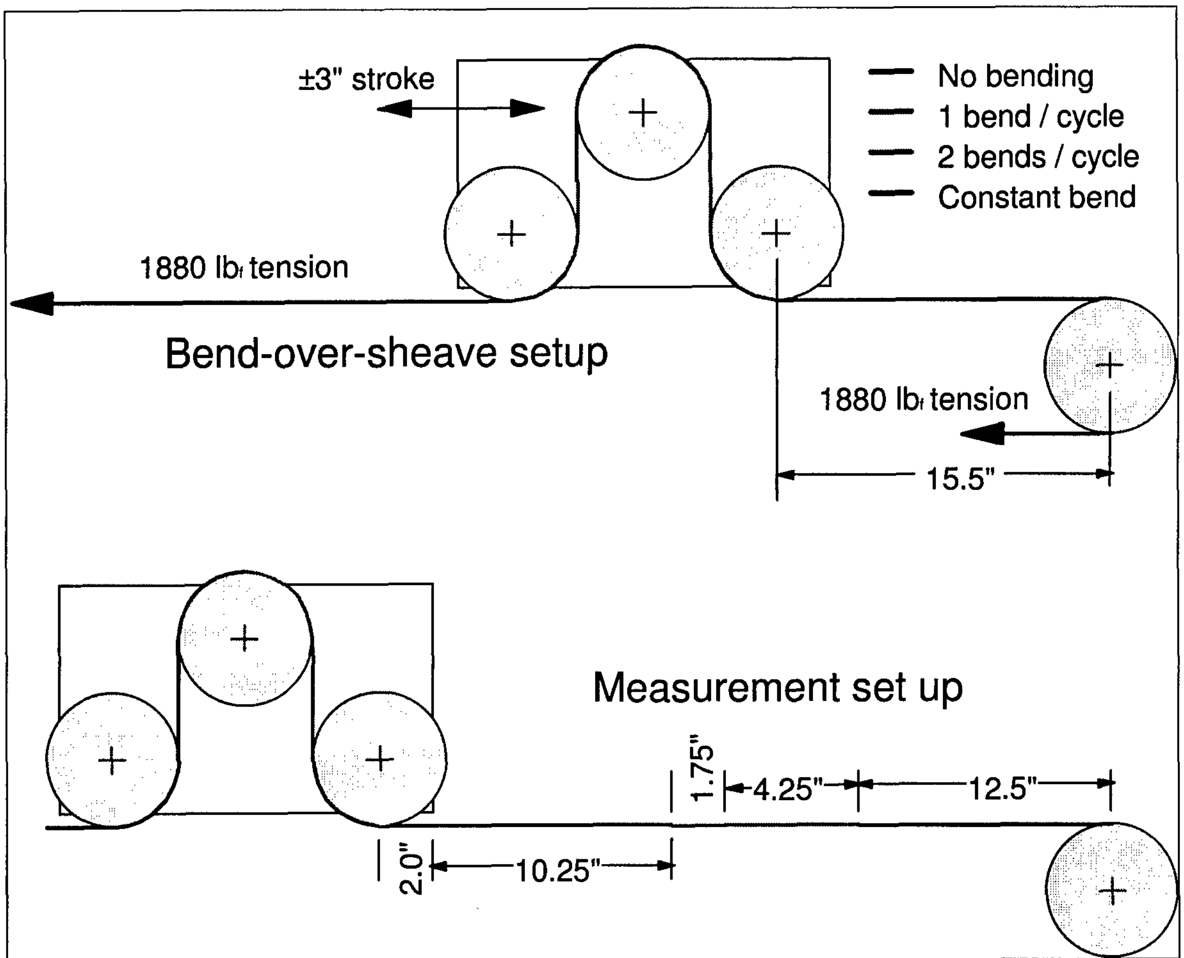

Figure 11: Experimental setup for monitoring rope damage in-situ.

4.2 Tests Results

Along side the rope testing, we are also gathered data on time domain resonance loss factor in worn ropes. As a synthetic rope is loaded and bent, the individual strands and fibers slide against one another as they reposition relative to their individual axial loads. The resulting abrasion causes increased surface contact due to the production of fibrules and other surface distortions. As these interacting surfaces get more and more entangled, the lossyness (1/Q) of the rope increases; meaning that the resonant frequency becomes less defined, or lower amplitude and wider bandwidth. A graph of Q for a Kevlar braided rope is shown in Figure 12. It can now be shown that a rope of known length under known load can have an estimated remaining life based on its measured Q compared to a baseline.

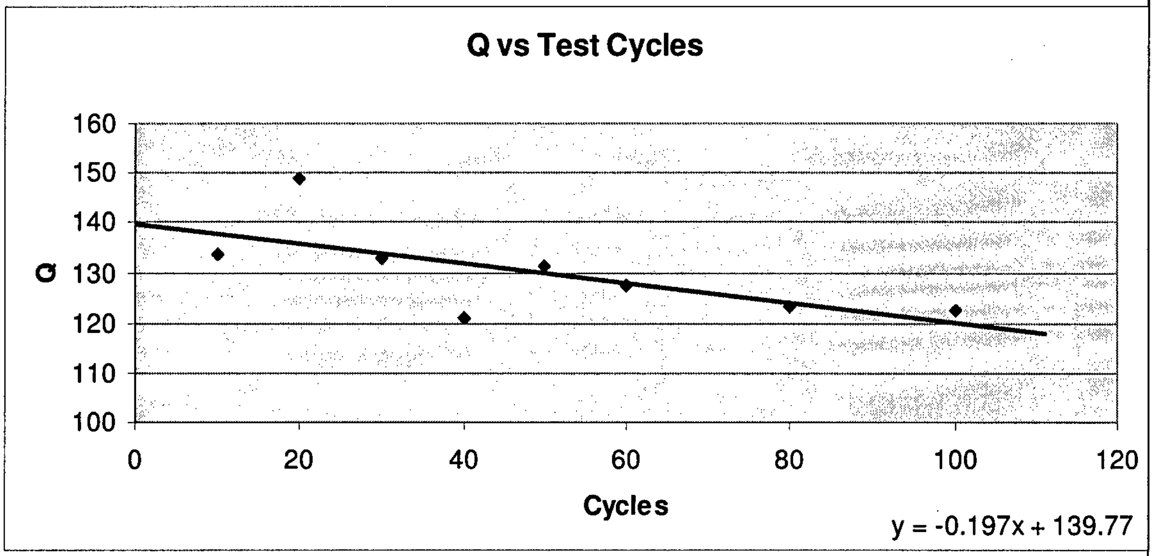

Figure 12: Strand construction showing elements of the yarn construction.

5 FEA Modeling

Following is a summary of the current FEA modeling parameters and results. The current model simulates a single fiber sliding along 6 outer fibers, which are wrapped around it. It is shown that the contact pressure is a maximum just before sliding and that contact pressure is not affected by the friction coefficient. Essentially this is a model of the single fiber test employed in Phase II. Although the single fiber test has been discontinued due to lack of repeatable results, this model is teaching us about fiber interaction at the most basic level in a rope. As mentioned earlier, testing results suggest a relationship between the orientation of the fibers in fiber-to-fiber abrasion and the surface condition. The goal of the modeling effort is to explore the optimum configuration and surface condition.

One-wrap & one-fiber model

- Geometry
  - Inner fiber: rigid body; Outer fiber: flexible body
- Loading condition (Two step)
  - 1st step(0<t<100): extension of outer fiber ($d_1 = 7.527\times e^{-3} mm$)
  - 2nd step(100<t<200): sliding of inner fiber ($d_2 = 1mm$)

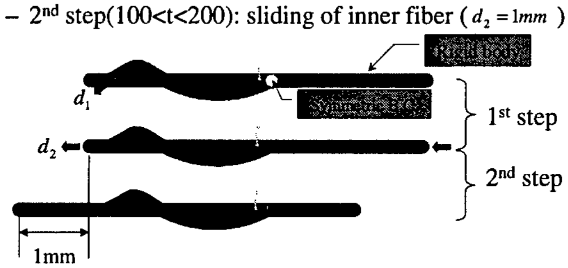

Figure 13: One-wrap & fiber Model;

Stress(σ_{zz}) distribution

- No friction (unit: kPa)

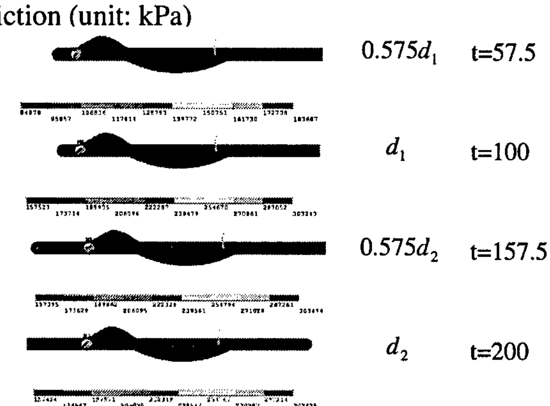

Figure 14: Stress distribution;

Total strain energy

- Effect of friction coefficient
  - 1st step(t<100): small strain energy
  - 2nd step(t>100):
    - Strain energy increases due to work done by friction force.

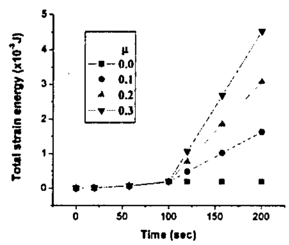

Figure 15: Total strain energy;

Contact stress

- Contact pressure

$$P = \begin{cases} 0 & if\ u_n > 0 \\ K_n u_n & if\ u_n < 0 \end{cases} \qquad \text{where } K_n : \text{contact normal stiffness}, \quad u_n : \text{contact gap size}$$

- Contact friction stress
  - By Coulomb's law

$$\tau_y = \begin{cases} K_s u_y & if\ \tau = \sqrt{\tau_y^2 + \tau_z^2} - \mu P < 0 \quad \text{(sticking)} \\ \mu K_n u_n & if\ \tau = \sqrt{\tau_y^2 + \tau_z^2} - \mu P = 0 \quad \text{(sliding)} \end{cases}$$

where K_s : tangential contact stiffness
u_y : contact slip distance in y direction
μ : frictional coefficient

Figure 16: Contact stress I;

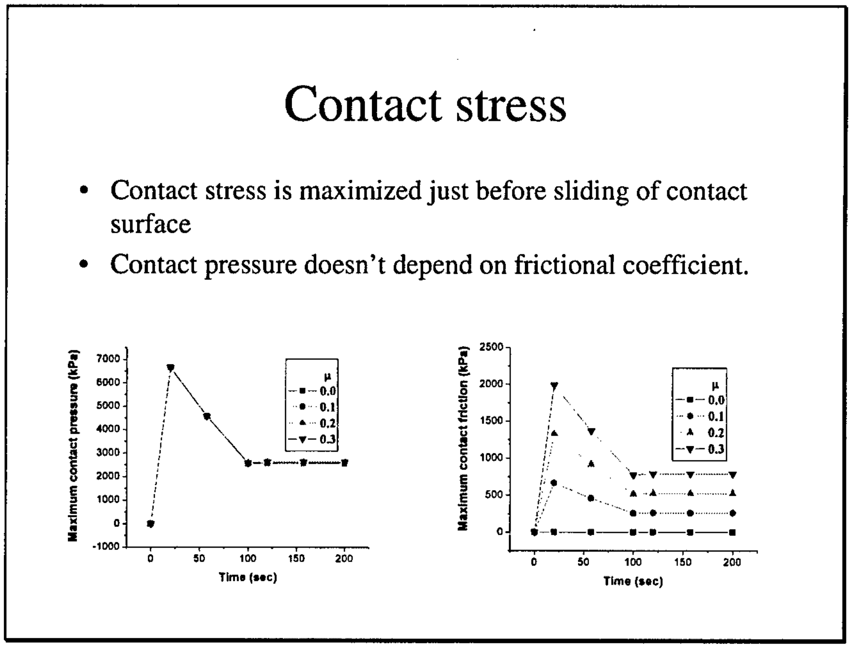

Figure 17: Contact stress II;

6 *Investigation of alternative materials*

Another approach that was explored is a dry Teflon coating. A company by the name of Toray Industries, Inc. coated Vectran yarn with a proprietary Teflon coating process that requires no elevated temperature cure. This yarn was tested by ADC with the results compared to baseline are listed in Figure 18. Results from this testing will be compared to the fluorosilane coatings already tested. One of the major concerns with the Teflon coating was the fact it was thick and easily broke off or rubbed off with little effort.

Vectran Coating	Average Cycles to Failure
(none)	529
fluorochemical urethane	1427
Teflon	5550
"10/6 solution" 5% TEOS 15%PDMS in Di(propylene glycol) dimethyl ether	29287

Figure 18: Teflon coating vs. baseline.

7 *Conclusions*

Impressive results in the yarn tests showed that there is great promise in creating a large scale synthetic rope that would outperform the existing wire rope. With more time and testing given to the manufacturing of this the new coated synthetic rope; a mainstream product could be used

in many military and commercial applications. This further research is proposed for phase II option 1. Finally product this would lead to a successful demonstration in Port Hueneme, CA.